

EXHIBIT D



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(54) **DIRECT DIGITAL CONVERSION TUNER
AND METHOD FOR USING SAME**

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(52) **U.S. Cl.** **455/324**; 341/126; 375/316

(58) **Field of Classification Search** 455/324;
341/126, 143, 155; 375/316
See application file for complete search history.

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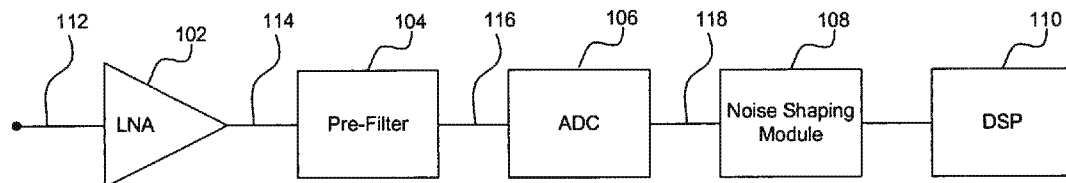
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(57) **ABSTRACT**

A direct sampling tuner includes a low noise amplifier and an
optional dynamically configurable band pass filter coupled to
the low noise amplifier. The optional filter is configured to
pass a selected band of channels. The tuner further includes a
relatively high accuracy, multi-bit analog-to-digital converter
("ADC") coupled to the LNA or to the optional dynamically
configurable band pass filter. The ADC operates at greater
than about twice a frequency of a sampled signal. The ADC
directly samples the spectrum of the selected channels at the
Nyquist frequency, thus avoiding image problems presented
by conventional tuners.

24 Claims, 1 Drawing Sheet

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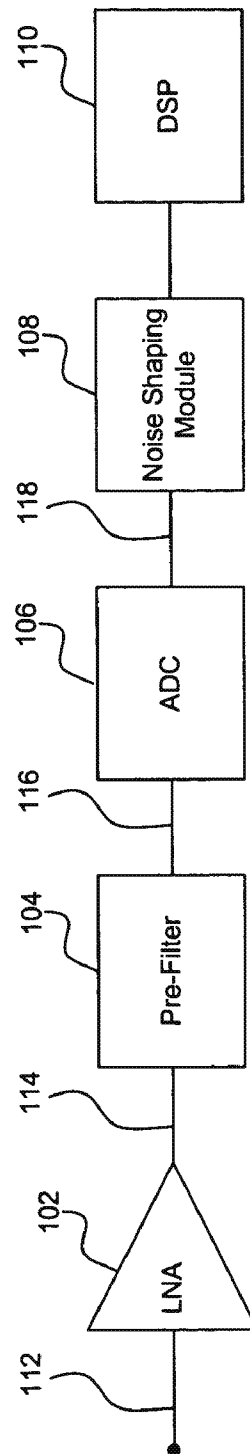


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**DIRECT DIGITAL CONVERSION TUNER
AND METHOD FOR USING SAME****CROSS REFERENCE TO RELATED
APPLICATIONS**

This application claims the benefit under 35 U.S.C. § 119 (e) to U.S. Provisional Application No. 60/537,025, filed Jan. 20, 2004, which is incorporated by reference herein in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to tuners.

2. Related Art

Radio frequency (RF) tuners extract information from a selected channel within a spectrum of available channels. RF tuners are used in, for example, cable modems, satellite set top boxes, cable set top boxes, and the like.

What are needed, therefore, are improved methods and systems for tuning an RF signal.

SUMMARY OF THE INVENTION

The present invention is directed to improved methods and systems for tuning. More particularly, the invention relates to direct sampling tuners. The invention can be implemented in, for example, cable modems, satellite set top boxes, cable set top boxes, and the like. The present invention reduces or eliminates mixers, SAW filters, and other analog components.

In accordance with one embodiment of the present invention, a direct sampling tuner includes a relatively high accuracy, multi-bit analog-to-digital converter ("ADC"). In this embodiment, the ADC operates at greater than twice the frequency of a sampled signal. The ADC directly samples a spectrum of selected channels at or above a Nyquist frequency.

In one example, a front end of the direct sampling tuner includes a low noise amplifier ("LNA"). In this example, an entire band is digitized so that the multiple channels can be demodulated using a digital signal processor ("DSP").

In another example, a front end of the direct sampling tuner includes a LNA and/or a dynamically configurable band pass filter. In the latter example, the filter is configured to pass a selected band of channels. Use of the filter in this latter example reduces the complexity required of the ADC.

In one example, the ADC directly samples the channels and passes the resultant multi-bit information to a digital signal processor for channel filtering and/or other processes.

In one example, multi-bit noise shaping is utilized to further reduce the complexity of the ADC.

Additional features and advantages of the invention will be set forth in the description that follows. Yet further features and advantages will be apparent to a person skilled in the art based on the description set forth herein or may be learned by practice of the invention. It is to be understood that both the foregoing summary and the following detailed description are exemplary and explanatory, and are intended to provide further explanation of the invention as claimed.

**BRIEF DESCRIPTION OF THE
DRAWINGS/FIGURES**

The present invention will be described with reference to the accompanying drawings, wherein like reference numbers

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may indicate identical or functionally similar elements. Also, the leftmost digit(s) of the reference numbers may identify the drawings in which the associated elements are first introduced.

The FIGURE is a block diagram of a direct sampling tuner, according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION**Introduction**

The present invention is directed to improved methods and systems for tuning an RF signal. More particularly, the invention is directed to direct sampling tuning for, among other things, cable modems, satellite set top boxes, cable set top boxes, and the like. Direct sampling is performed at or above the Nyquist rate, or at a sub-sampling rate.

Throughout this description "direct sampling" refers to sampling of a received signal, as opposed to systems that frequency down-convert a received signal prior to demodulation.

The invention includes multiple features that can be implemented alone and/or in various combinations with one another.

Exemplary Tuners

Tuners discriminate between available channels by filtering out unwanted channels. It is generally impractical to filter at higher frequencies because the necessary filter agility and narrowness is prohibitively expensive at higher frequencies. Instead, conventional tuners mix received signals with a lower frequency clock signal to generate lower frequency replicas or images of the received signals. The lower frequency signals are then filtered to obtain the desired signal or channel. The desired signal or channel is then sampled or demodulated to extract the desired channel information therein.

Conventional tuners include heterodyne-based tuners (including super heterodyne-based tuners), which use mixers for the down-conversion process. Mixers essentially sample the modulated signal at less than the Nyquist rate. However, this can cause well known imaging problems. The imaging problems are typically overcome with SAW filters (standing acoustic wave filters). SAW filters have significant losses, so additional gain stages are required. The additional gain stages consume additional power and contribute to poor noise figures. In addition, non-ideal and non-uniform operating characteristics associated with these and other analog components in heterodyne-based tuners make component layout burdensome. For example, placement and interconnection of the SAW filters affect the overall performance of the tuner. As a result, heterodyne-based tuners tend to be expensive in terms of the number of components required, manufacturing efforts, and power consumption.

Conventional tuners also include direct conversion and low IF (intermediate frequency) tuners, in which a mixer is utilized to convert a modulated signal directly to baseband or to a very low frequency. Direct conversion tuners avoid intermediate stages that are normally associated with heterodyne-based tuners, but they also utilize mixers. As a result, low IF tuners also suffer from images, which require significant down-stream correction circuitry. A problem in direct conversion tuners is harmonic mixing where harmonics of the local oscillator frequency mix undesired channels to a baseband on top of the channel of interest. This is especially a problem for broadband signals, such as cable and satellite.

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Exemplary Direct Sampling Tuners

The Figure is a block diagram of a tuner **100**, according to one embodiment of the present invention. Tuner **100** includes a direct sampling analog-to-digital converter ("ADC") **106**. The ADC **106** samples a signal **116** at a Nyquist frequency (i.e., greater than twice the frequency of the signal **116**). As a result, image problems associated with conventional tuners are substantially eliminated.

A front end of the tuner **100** includes a low noise amplifier ("LNA") **102**. The LNA **102** amplifies a received signal **112**.

In one example, the front end of the tuner **100** also includes a pre-filter **104**. The pre-filter **104** is a dynamically configurable pre-filter, configured to pass a selected band of the amplified signal **112** to the ADC **106**.

In one example, the tuner **100** further includes a noise-shaping module **108**, which improves the resolution of the output **118** of the ADC **106**.

In one example, the tuner **100** further includes a digital signal processor ("DSP") **110**. In one example, an entire band received at the ADC **106** is digitized so that multiple or desired channels of the band can be demodulated using the DSP **110**.

In this embodiment, the tuner **100** eliminates many of the analog components of conventional tuners, such as mixers, SAW filters, and multiple power-consuming gain stages. This, in turn, reduces manufacturing efforts and component costs. The reduced number of analog components improves the manufacturability of the tuner **100** because digital systems can be manufactured in quantity without the system variabilities that come with analog manufacturing. The reduction of analog components also provides operational power savings over conventional tuners because frequency synthesizers, mixers, SAW filters are not necessary. The reduced number of stages in the tuner **100** (i.e., the LNA **102** is substantially the only gain in the front end) provides improved noise figures.

Exemplary High Speed, High Resolution ADC

In one example, the direct sampling ADC **106** is a high speed, high resolution ADC that effectively samples the entire spectrum of the signal **116** at the Nyquist rate.

For example, in a cable channel environment, where the highest frequency is typically around 860 MHz, the ADC **106** is operated at greater than 1720 MHz. Also, for example, in a satellite environment, where the frequency is about 2150 MHz, the ADC **106** is operated at greater than 4300 MHz. In one example, in order to operate the ADC **106** at one or more of these speeds, the ADC **106** is implemented in an open loop system, i.e., without feedback. In one example, corrections can be implemented downstream in the DSP **110**.

In one example, the ADC **106** is a multi-bit ADC. In a cable channel environment the ADC **106** can be, for example, a 10 bit ADC, that can yield ENOB (effective number of bits) of 8 bits. ENOB is the measured performance (in bits) of the ADC **106** with respect to input frequency f_{IN} . As f_{IN} increases, overall noise (particularly the distortion components) also increases, thereby reducing the ENOB and SINAD (signal-to-noise and distortion ratio). ENOB is related to SINAD by the following equation:

$$ENOB = \frac{SINAD - 1.76}{6.02}$$

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In a satellite environment, the ADC **106** can be a 12 bit ADC. As described below, noise shaping can be employed to reduce the number of bits in the ADC **106**, without loss of accuracy.

It is to be appreciated that the ADC **106** can be any number of bits, and respectively, any ENOB, depending on its application and/or environment.

In various examples described below, the ADC **106** is implemented in one or more of a variety of ways.

In one example, the ADC **106** is implemented as a flash ADC. Flash ADCs are well known to those skilled in the art. A Flash ADC uses a series of comparators with different threshold voltages to convert an analog signal to a digital output.

In one example, the ADC **106** is implemented as a sample and hold circuit. Such a sample and hold can be implemented with 2^n comparators, where n represents the number of bits in the ADC **106**. Sample and hold circuits and comparators are well known to those skilled in the art.

Another example implementation for the ADC **106** is a pipeline ADC or subranging quantizer. Pipeline ADCs are well known to those skilled in the art. A pipeline ADC uses two or more steps of subranging. First, a coarse conversion is done. In a second step, the difference to the input signal is determined with a digital to analog converter (DAC). This difference is then converted finer, and the results are combined in a last step. This type of ADC is fast, has a high resolution and only requires a small die size. As another explanation, pipeline ADCs consist of numerous consecutive stages, each containing a track/hold (T/H), a low-resolution ADC and DAC, and a summing circuit that includes an inter-stage amplifier to provide gain.

In one example, the ADC **106** "sub-samples" the signal **116**. Sub-sampling refers to sampling of the signal **116** at less than the Nyquist rate with respect to the carrier frequency of the signal **116**, but at the Nyquist rate with respect to the information modulated thereon. For example, for channel having a carrier frequency at 860 MHz, the bandwidth of the channel is typically in the range of 6 Mhz wide. Thus, while the ADC **106** sub-samples the carrier, it over samples the modulating information.

The ADC **106** outputs samples **118**, which are processed digitally in the DSP **110** to extract the information from a desired channel. The DSP **110** performs one or more of a variety of operations on the sampled information, as described below.

The ADC **106** is optionally implemented in an interleaved fashion as described in, for example, U.S. patent application Ser. No. 10/085,071 ("the '071 application") (that published Jun. 27, 2002 as U.S. Published Application No. 2002-0080898 A1), entitled, "Methods and Systems for DSP Based Receivers," filed on Mar. 1, 2002, and incorporated herein by reference in its entirety.

LNA and Optional Pre-Filter

The received signal **112** is typically a relatively weak signal. The LNA **102** increases the amplitude and/or power of the signal **112** so that it can be processed within the tuner **100**. For example, the LNA can be designed to bring the signal **112** up to about 1 volt so that it is big enough to fill substantially all the codes in the ADC **106**. ADC codes are well known to those skilled in the relevant art.

Optional pre-filter **104** is utilized to reduce the complexity of the ADC **106**. As described above, the ADC **106** samples the spectrum of the signal **116**. When the optional pre-filter **104** is omitted, the spectrum of signal **116** is effectively the spectrum of a received signal **112**. Omission of the pre-filter

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104 is typically suitable when the spectrum of interest in the received signal **112** is relatively narrow or when you want to demodulate multiple channels. When the spectrum of interest in signal **112** is relatively broad, however, the pre-filter **104** is optionally utilized to reduce the spectrum sampled by the ADC **106**.

For example, in a cable tuner environment, there can be up to 135 channels, or more, within the signal **112**. The pre-filter **104** is optionally implemented as a dynamically configurable band pass filter that passes a selectable band of interest, or sub-set of the channels, to the ADC **106**. This reduces the linearity, dynamic range, and number of bits required of the ADC **106**. In other words, pre-filter **104** reduces the required complexity of the ADC **106**.

In one example, the pre-filter **104** can be implemented as a digitally selectable bank of filters, each filter having a different pass band.

In an example using the pre-filter **104**, it provides the selected band of interest, or sub-set of channels, to the ADC **106**, which directly samples the selected band of interest. The samples are then processed by the DSP **110** to decode information from one or more selected channels.

In one example, the pre-filter **104** and the LNA **102** are integrated on a same integrated circuit chip. In other examples, the circuit chip can also include additional elements illustrated in THE FIGURE.

In one example, the LNA **102** includes autonomous gain control, which will keep the output **114** at a relatively fixed voltage level so that substantially all the codes in the ADC **106** are filled.

Optional Noise Shaping

In one example, noise shaping module **108** performs noise shaping on the output bits **118** of the ADC **106**. This allows the ADC **106** to be implemented with fewer bits without loss of accuracy. For example, when X bits are desired (X=1, 2, 3, . . .) the ADC **106** is implemented as a X-Y bit ADC (Y=1, 2, 3, but is always less than X) along with noise shaping module **108**.

In one example, noise shaping is performed on very low bit samplers, such as 1 or 2 bit samplers. In order to perform noise shaping on higher bit samplers, a relatively high accuracy digital to analog converter ("DAC") is needed in the noise-shaping module **108**. In other words, noise shaping is performed to a relatively high resolution.

Digital Signal Processing

The DSP **110** can be implemented in one or more of a variety of ways and with one or more of a variety of features. For example, and without limitation, the DSP **110** can perform one or more of: channel filtering, equalization, demodulation, decimation, and/or gain control.

In the example using the noise-shaping module **108**, in one example the noise shaping module is incorporated within the DSP **110**.

In one example, the LNA **102** and/or the pre-filter **104** can be implemented on a chip with the DSP **110**.

Additional features that can be implemented in the DSP **110**, alone and/or in various combinations with one another, are taught in, for example, the '071 application, which is discussed and incorporated by reference above.

CONCLUSIONS

The present invention has been described above with the aid of functional building blocks illustrating the performance of specified functions and relationships thereof. The boundaries of these functional building blocks have been arbitrarily

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defined herein for the convenience of the description. Alternate boundaries can be defined so long as the specified functions and relationships thereof are appropriately performed. Any such alternate boundaries are thus within the scope and spirit of the claimed invention. One skilled in the art will recognize that these functional building blocks can be implemented by discrete components, application specific integrated circuits, processors executing appropriate software and the like and combinations thereof.

While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

What is claimed is:

1. A direct sampling tuner for receiving an RF signal having multiple channels, comprising:

- a low noise amplifier arranged at a front end of the tuner and configured to be a first element to receive the RF signal and then to amplify the RF signal;
- a dynamically configurable band pass filter coupled to the low noise amplifier, and configured to pass a selected band of the multiple channels of the amplified RF signal; and
- a multi-bit analog-to-digital converter coupled to the dynamically configurable band pass filter, wherein the analog-to-digital converter operates at greater than twice a frequency of the selected band of the multiple channels of the amplified RF signal.

2. The tuner according to claim 1, wherein the analog-to-digital converter comprises between an 8 to 12 bit analog-to-digital converter.

3. The tuner according to claim 1, further comprising a noise shaping module coupled to the analog-to-digital converter.

4. The tuner according to claim 3, wherein the analog-to-digital converter comprises between an 8 to 12 bit analog-to-digital converter.

5. The tuner according to claim 3, further comprising a digital signal processor coupled to the noise shaping module.

6. The tuner according to claim 1, wherein the analog-to-digital converter operates at greater than 1 GHz.

7. The tuner according to claim 1, wherein the analog-to-digital converter comprises one of a flash or pipeline analog-to-digital converter.

8. The tuner according to claim 1, wherein the analog-to-digital converter comprises a sample and hold module and 2ⁿ comparators, wherein n equals a number of bits in the sample and hold module.

9. The tuner according to claim 1, wherein the analog-to-digital converter comprises a multiple-stage pipeline analog-to-digital converter wherein each stage of the multiple-stage pipeline analog-to-digital converter comprises one or more bits.

10. The tuner according to claim 1, wherein the analog-to-digital converter comprises an open loop analog-to-digital converter.

11. The tuner according to claim 1, wherein the low noise amplifier and the dynamically configurable band pass filter are implemented on a single integrated circuit.

12. The tuner according to claim 1, wherein the tuner is incorporated within a cable modem.

13. The tuner according to claim 1, wherein the tuner is incorporated within a cable set top box.

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14. The tuner according to claim 1, wherein the low noise amplifier comprises an autonomous gain control configured to keep an output of the low noise amplifier at a fixed voltage level.

15. A method for tuning an RF signal having multiple channels using a direct sampling tuner, comprising:
 5 initially receiving the RF signal at a low noise amplifier arranged at a front end of the tuner;
 amplifying the multiple channels of the RF signal using the amplifier;
 10 filtering, using a digitally selectable bank of filters, all but a sub-set of channels from the amplified multiple channels;
 converting the sub-set of channels to a multi-bit digital signal, wherein said converting is performed at a sample rate that is greater than twice a frequency of a highest frequency in the sub-set of channels; and
 15 digitally processing the multi-bit digital signal to obtain information from the sub-set of channels.

16. The method according to claim 15, wherein said converting comprises converting the sub-set of channels to between an 8 to 10 bit digital signal.

17. The method according to claim 15, further comprising noise shaping the multi-bit digital signal.

18. The method according to claim 17, wherein said converting comprises converting the sub-set of channels to between an 8 to 10 bit digital signal.

19. The method according to claim 15, wherein said converting is performed at or above 1 GHz.

20. The method according to claim 15, wherein said converting comprises interleaving.

21. The method according to claim 15, wherein the digital processing comprises one or more of channel filtering, equalization, demodulation, decimation, and/or gain control.

22. A direct sampling tuner for receiving an RF signal having multiple channels, comprising:

a low noise amplifier arranged at a front end of the tuner and configured to be a first element to receive the RF signal and then to amplify the RF signal;
 a filter configured to receive the amplified RF signal having the multiple channels;

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a multi-bit analog-to-digital converter coupled to the filter, wherein the analog-to-digital converter operates at greater than twice a frequency of a selected band of the multiple channels of the amplified RF signal; and

a digital signal processor that is used to demodulate the selected band of the multiple channels of the amplified RF signal.

23. A method for tuning an RF signal having multiple channels using a direct sampling tuner, comprising:

initially receiving the RF signal at an amplifier arranged at a front end of the tuner;

amplifying the multiple channels of the RF signal using the amplifier;

filtering the amplified multiple channels;

converting the filtered multiple channels to a multi-bit digital signal, wherein said converting is performed at a sample rate that is greater than twice a frequency of a highest frequency in the filtered multiple channels;

noise shaping the multi-bit digital signal; and

demodulating the noise shaped multi-bit digital signal to obtain information from one or more of the multiple channels.

24. A direct sampling tuner for receiving an RF signal having multiple channels, comprising:

a low noise amplifier arranged at a front end of the tuner and configured to be a first element to receive the RF signal and then to amplify the RF signal;

a dynamically configurable band pass filter coupled to the low noise amplifier, and configured to pass a selected band of the multiple channels of the amplified RF signal; and

a multi-bit analog-to-digital converter coupled to the dynamically configurable band pass filter, wherein the analog-to-digital converter operates at less than twice a carrier frequency of the selected band of the multiple channels, but at greater than twice a frequency of an information modulated on the selected band of the multiple channels.

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